# The Interaction of Nonlinear Internal Waves with Other Processes

Chris Garrett
Department of Physics and Astronomy
Elliott Building
University of Victoria
P.O. Box 3055
Victoria, BC
Canada, V8W 3P6

phone: (250) 721-7702 fax: (250) 721-7715 email: cgarrett@uvic.ca

Award Number: N00014-05-1-0285 http://maelstrom.seos.uvic.ca/

## **LONG-TERM GOALS**

To understand and parameterize small-scale ocean processes.

To understand ocean tides and their effects.

To understand surface wave processes.

## **OBJECTIVES**

To elucidate and quantify the back effect on internal waves, and other motions, of refracted and breaking surface waves.

To understand ocean tides and to quantify the power available from exploitation of strong tidal currents.

To understand aspects of extreme and unexpected surface waves.

## **APPROACH**

Recent studies have been largely analytical, with support from numerical evaluation.

## WORK COMPLETED

Progress has been made in adding dissipation to studies of the interaction between surface waves and currents.

The reason for the extreme tide of Ungava Bay has been discovered. General results on the maximum power obtainable from tidal currents have been derived.

A review of extreme events has been completed. The frequency of occurrence of unexpectedly large surface waves has been evaluated.

maintaining the data needed, and c including suggestions for reducing	lection of information is estimated to ompleting and reviewing the collect this burden, to Washington Headqu uld be aware that notwithstanding an DMB control number.	ion of information. Send comments arters Services, Directorate for Info	s regarding this burden estimate ormation Operations and Reports	or any other aspect of the s, 1215 Jefferson Davis	nis collection of information, Highway, Suite 1204, Arlington	
1. REPORT DATE 30 SEP 2007 2. REPOR		2. REPORT TYPE		3. DATES COVERED <b>00-00-2007</b> to <b>00-00-2007</b>		
4. TITLE AND SUBTITLE				5a. CONTRACT NUMBER		
The Interaction of Nonlinear Internal Waves with Other Processes				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  University of Victoria, Department of Physics and Astronomy, Elliott Building, Victoria, BC Canada, V8W 3P6,				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAIL Approved for publ	ABILITY STATEMENT ic release; distributi	on unlimited				
13. SUPPLEMENTARY NO	TES					
14. ABSTRACT						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	Same as Report (SAR)	4		

**Report Documentation Page** 

Form Approved OMB No. 0704-0188

## **RESULTS**

The effect of currents on surface waves is simply described by wave action conservation, modified to allow for wave dissipation. The vertically-integrated effect of the surface waves on the current may be described in terms of radiation stress divergence if the mean current is taken to include the mass transport associated with the Stokes drift. This approach may be suitable for shallow water waves, but in deep water it seems more appropriate to treat the Stokes drift separately. The effect of the waves on the underlying current may then be described in terms of a vertically-integrated vortex force, some mass exchange between the varying Stokes drift and the mean flow, and a force related to wave dissipation. This is all (decades) old. The new advance is to quantify the force associated with dissipation assuming a limiting wave steepness, and to evaluate it for wave encountering an adverse current. It scales with the third or fourth power of the phase speed of the waves and can be significant, comparable with the wind stress over an extensive fetch.

In collaboration with others, I have shown how the very large tides in Ungava Bay are associated with a resonance at approximately 12.7 hours, close to the M<sub>2</sub> tidal period of 12.4 hours. This is important as the Ungava Bay/Hudson Strait region has more tidal dissipation than any other region in the world.

I have also derived results for the maximum power available from turbines in tidal streams, and shown what losses are associated with the merging of the turbine wakes and the surrounding free stream.

As part of ongoing involvement in the study of rogue waves and other extreme events, Johannes Gemmrich and I have investigated the phenomenon of "unexpected" waves that can occur even in Gaussian seas, without the resonant nonlinear interactions often invoked in the study of rogue waves. The argument is that a large wave after a calm period can be of greater concern than an extreme wave which is not much larger than those preceding it. Figure 1 shows that even with purely linear superposition of random waves from a JONSWAP spectrum for fully-developed seas, a wave has arisen with a crest height more than twice as large as any in the preceding 43 wave periods.

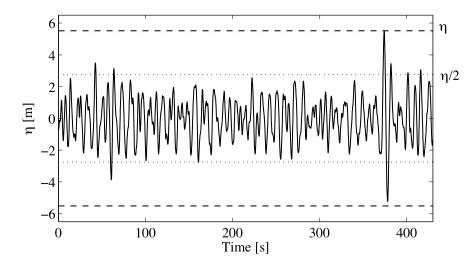


Figure 1. Synthetic time series for the sea surface displacement from random superposition of waves from a JONSWAP spectrum for fully-developed seas with a peak period of 10 seconds. A large wave at 374 seconds has a crest more than twice as high as that of any wave in the preceding 310 seconds. This is 43 times the average wave period of 7.1 seconds.

Monte Carlo simulations give the recurrence time for any wave a given factor higher than any of a given number of preceding waves, for wave height from trough to crest, crest height, and crest height with enhancement to allow for nonlinear but non-resonant second order effects. For example, a wave crest twice as high as any of the preceding 30 will occur once every 4 days if the peak period is 10 seconds. The return period is reduced to 2 days if allowance is made for nonresonant nonlinear interactions changing the shape. The return period is also reduced if one or more precursor waves are allowed for.

## **IMPACT/APPLICATIONS**

Results on wave current interaction will impact on studies of internal waves, eddies, and fronts.

Results on tidal power are relevant to discussions of renewable energy.

Results on unexpected waves can be incorporated into warning systems.

#### RELATED PROJECTS

The projects described above have also been supported by Canadian funding agencies. A related project supported entirely by Canadian agencies concerned breaking surface waves.

## **PUBLICATIONS**

Baschek, B., D. M. Farmer, and C. Garrett. 2006. Tidal fronts and their role in air-sea gas exchange. *J. Mar. Res.* 64, 483-515. [published, refereed]

Inoue, R. and C. Garrett. 2006. Fourier representation of quadratic friction. *J. Phys. Oceanogr.* 37, 593-610. [published, refereed]

Garrett, C. and T. Gerkema. 2006. A note on the bodyforce term in internal-tide generation. *J. Phys. Oceanogr.* 37, 2172-2175. [published, refereed]

Garrett, C. and E. Kunze. 2006. Internal tide generation in the deep ocean. *Ann. Rev. Fluid Mech.* 39, 57-87.[published, refereed]

Sutherland, G., M. Foreman, and C. Garrett. 2006. Tidal current energy assessment for Johnstone Strait, Vancouver Island. *J. Power and Energy* 221, 147-157. [published, refereed]

Garrett C. 2007. Robert William Stewart. *Biographical Memoirs of Fellows of the Royal Society* 52, 349-363. [published, refereed]

Garrett, C. and P. Cummins. 2007. The efficiency of a turbine in a tidal channel. *J. Fluid Mech.* 588, 243-251. [published, refereed]

Arbic, B. K., P. St-Laurent, G. Sutherland and C. Garrett. 2007. On the resonance and influence of the tides in Ungava Bay and Hudson Strait. *Geophys. Res. Lett.* 34, L17606, doi:10.1029/2007GL030845. [published, refereed]

Müller P. and C. Garrett. 2007. Rogue waves: An introductory example. *Proceedings of the Fifteenth 'Aha Huliko'a Hawaiian Winter Workshop* [in press].

Garrett, C. and P. Müller. 2007. Extreme events. *Proceedings of the Fifteenth 'Aha Huliko'a Hawaiian Winter Workshop.* [in press].

Gemmrich, J. R., M. L. Banner and C. Garrett. 2007. Spectrally resolved energy dissipation and momentum flux of breaking waves. *J. Phys. Oceanogr.* 

Blanchfield, J., C. Garrett, P. Wild, and A. Rowe. 2007. The extractable power from a channel linking a bay to the open ocean. *J. Power and Energy*.

Gemmrich, J. and C. Garrett. 2007. Unexpected waves. Geophys. Res. Lett.